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OPTOELECTRONIC PHASE DELAY MEASUREMENT FOR A MODIFIED MICHELSON INTERFEROMETER

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Abstract – For the primary calibration of the phase response of accelerometers, the knowledge of the response delay of the reference, i.e. the laser interferometer is a decisive prerequisite. However, an experimental determination of the interferometric response time is not a simple task.
This contribution describes an opto-electronic set-up based on a femtosecond laser and originally developed for calibration of high speed sampling oscilloscopes, which enables a precise determination of the intrinsic delay of the photo detectors of a modified Michelson interferometer used at PTB.

Keywords phase response, laser interferometer, response time

1. INTRODUCTION

The primary calibration of the phase response of accelerometers becomes increasingly important for the traceability of acceleration. For the calibration measurement this necessitates the precise determination of the response time of the accelerometer from the input acceleration signal to the electrical output in terms of typically charge or voltage. However, the input acceleration is not directly accessible during primary calibration, rather it is determined by laser interferometric measurements as a reference linking the acceleration to the optical wavelength of the laser and the time, determined by the sampling of the electric output of a photo detector. This in turn means that the response time of the photo-detector might have a strong influence on the overall phase response of the calibration results.
Fig. 1 shows a typical set-up for the primary calibration of accelerometers with a modified Michelson interferometer. For details on the method please refer to [1, 2]. From the two photodiode time series $I(t)$ and $Q(t)$ the interferometer (acceleration) time series $i(t)$ is calculated by the so called sine approximation (method 3 of [1]). In order to determine the phase delay of the accelerometer's response

$$\varphi_{ua} = 2\pi \cdot f \cdot (t_u - t_a) \qquad (1)$$

the time difference

$$t_u - t_a = (t_u - ti) + (t_i - t_a) \qquad (2)$$

has to be determined.

In Eq. (1) and (2) the quantity f is the mechanical vibration frequency and t_x is the time delay of the signal $x(t)$ with respect to the measurement start, (c.f. Fig. 2).

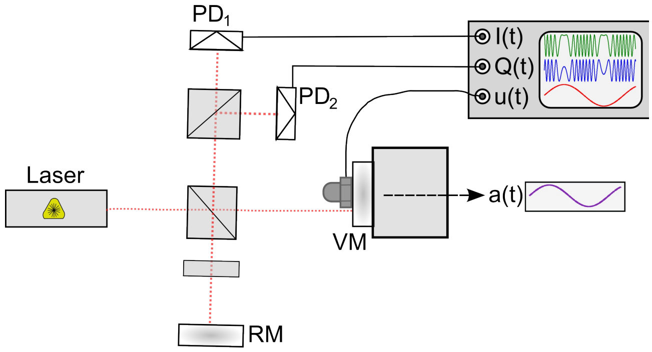

Fig. 1 Typical set-up of a modified Michelson interferometer for the primary calibration of accelerometers with trace of the photodiode (PD) signals $I(t)$ and $Q(t)$, the electrical output of the accelerometer $U(t)$ and the (unknown) input acceleration $a(t)$. VM is a vibrating mirror, RM is the reference mirror.

The first term on the right side of (2) is determined in every individual calibration measurement of an accelerometer, the second term (t_i - t_a), however, is a systematic term of the interferometer. It includes the optoelectronic phase delay of the photo detectors with their embedded pre-amplifiers.

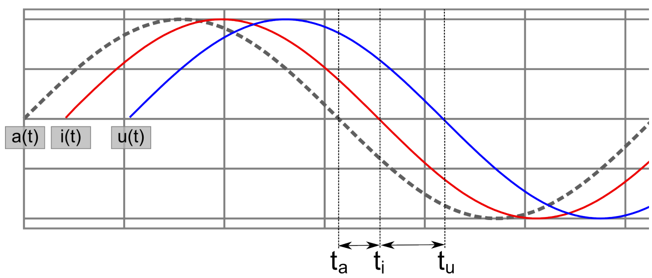

Fig. 2 Time series used for the primary calibration with their respective relative delay in the time domain. With $i(t)$ being the measured acceleration, $u(t)$ the electric output and $a(t)$ the (unknown) true acceleration (dashed line).

2. EXPERIMENTAL DETERMINATION OF THE PHASE DELAY

In order to determine the response of the photo detectors used in the above mentioned interferometer a technology is applied which is usually used to characterize ultra fast sampling oscilloscopes (UFSO) with a bandwidth of several 10 GHz.

The setup (c.f. Fig. 3) makes use of a mode locked femto-second laser (FSL) which runs with a repetition rate of 76 MHz providing pulse durations of 200 fs. The pulses of the FSL are split by a beam splitter in order to have one beam line providing the trigger and the second beam line providing the input for either a photoconductive switch (PCS) as the reference or the photo detector under test (DUT).

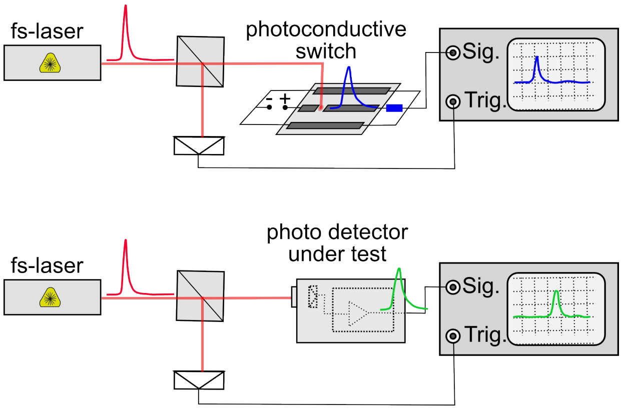

Fig. 3 Set-up for the determination of the phase delay by a substitution method. The photoconductive switch (upper part) is the reference and is sub-sequently replaced by the device under test (lower part).

The PCS was extensively studied [3] for its original purpose (the characterization of UFSO). Therefore its response time is well known with an uncertainty below 100 ps. Considering the requirements from accelerometry, this would correspond to a phase uncertainty of less than 0.001° at 20 kHz.

In subsequent measurements the phase delay of the DUT can now be determined as follows. In a first series of repeated measurements the electric response of the PCS to the second beam line of the FSL pulses is measured with an UFSO (upper part of Fig. 3). The UFSO is triggered with a fast photo diode in the first beam line. From the peak position of the signal trace a time delay between the trigger and the signal from the PCS can be determined.

In a second series of measurements the same procedure is repeated with the DUT replacing the PCS (lower part of Fig. 3). Again a time delay can be determined between the peak position of the signal trace and the trigger. The intrinsic phase delay term for the photo detector of the interferometer (the DUT), $(t_i - t_a)$ of (2), is then basically given by the difference of the two measured time delays.

3. EXPERIMENTAL RESULTS

Since the PCS was especially designed for measurements with GHz-bandwidth, its response to the FSL pulse is a sharp peak in the trace of the UFSO. The photodiodes, in turn, are specified with a comparatively limited bandwidth of 300 MHz and therefore broaden the input pulse considerably. In order to visualize the results of the delay measurements, Fig. 4 depicts a typical (normalized) FSL pulse after conversion with the PCS and sampling with the UFSO.

The full width at half maximum (FWHM) of the PCS converted pulse is approx. 11 ps. Fig. 5 depicts a com-bination of the two subsequent measurement series. The broadened pulse response of the photo detectors under test is clearly visible as their FWHM is of the order of 1.1 ns

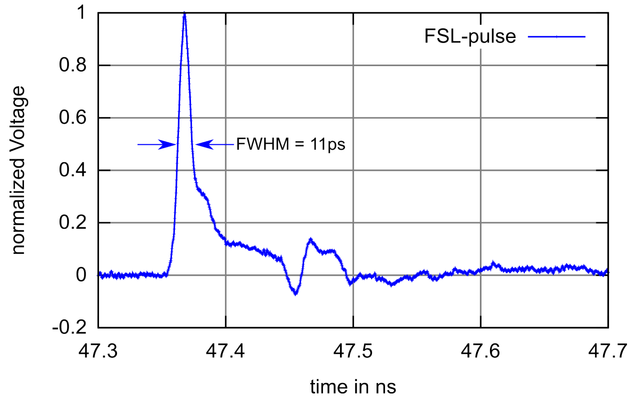

Fig. 4 Trace of a FSL pulse converted by the PCS and sampled with the UFSO

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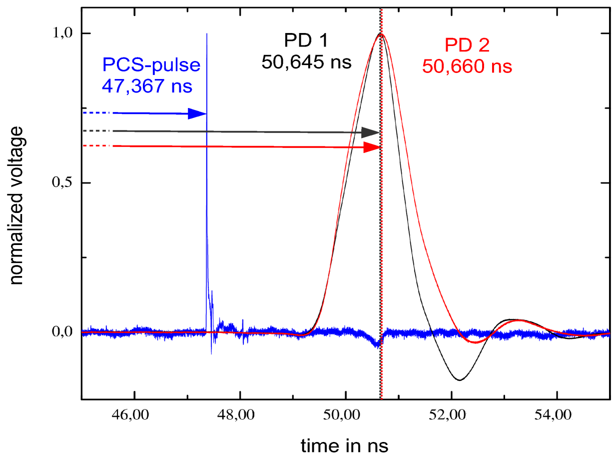

Fig. 5 Combined picture of the FSL pulse measured via the PCS and the FSL pulse measured with either of the Photo diodes under test on the same time scale. The times in the picture are the delay sincetriggering of the UFSO.

For the purpose of the allocation of a distinctive delay time with respect to the trigger, the position of the peak value of the response traces was determined. In the case of the PCS the time of the maximum (t_{PCS}) could be determined within the range of 2 ps without problem, which is far below the overall measurement uncertainty, as it will become clear later.

For the response of the two photo detectors, the position of the maximum was not as clear, therefore, a Gaussian function was approximated by least squares fitting to adapt to the curve in the top 1 % of the sampled voltages (c.f. Fig. 6). The abscissa $(t_{PD_{1,2}})$ of the peak of the fitted Gaussian function was taken as the delay from the trigger of the photo detectors under test. In order to calculate the net delay of the photo detectors the travel time of the electrical pulse on the PCS $(t_{trav.PCS})$ and in an adapter $(t_{trav.\ adapt.})$ used for the connection of the photo detector to the UFSO were the final components needed. In order to determine this values the PCS and, similarly, the adapter were short-circuited and in a special measuring mode of the UFSO the double-traversal time of a pulse excitation was determined. In this mode the UFSO induces a short electrical pulse into the output of the PCS. This pulse is reflected at the shortened input terminal of the PCS and reenters the terminal of the UFSO after traversing the PCS (or the adapter) twice. The time between pulse excitation and the return in the PCS was determined to be 0.236 ns the traversal time for the adapter accounted to 0.800ns.

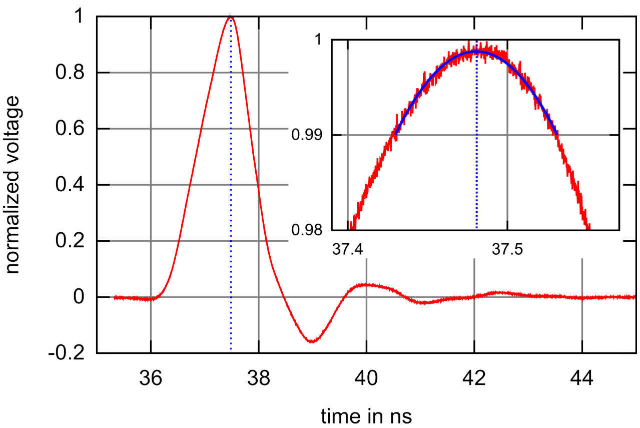

Fig. 6 example trace of the response of the photo detectors under test. The inlay shows the upper 2 % of the curve with the Gaussian function fitted to the peak values in order to allocate the peak position on the time axis.

The standard uncertainties related to the different time components were estimated as follows:

1. Uncertainty of the maximum of the PCS pulse $U(t_{PCS}) = 2$ ps .
2. Uncertainty of the maximum of the PD pulse $U(t_{PD}) = 20$ ps ,
   this covers the deviation between the two DUTs.
3. Uncertainty of the measurement of the traversal time
   $U(t_{Trav\_PCS}) = U(t_{Trav\_adapt.}) = 20$ ps .

In addition a variation of the trigger delay of the UFSO due to variations in the laser intensity was observed which was attributed with the uncertainty of

$$U(t_{trig}) = 15 \text{ ps} .$$

Adding everything up the total time delay caused by the PDs in the interferometric calibration set-up is

$$t_i = (t_{PD_{1,2}} - t_{trav.\ adapt.}) - (t_{PCS} - t_{trav.\ PCS}) \leqslant 3.10 \text{ ns}$$

with an expanded uncertainty of

$$W(t_i) = k \cdot U(t_i) \leqslant 80 \text{ ps} ,$$

applying a coverage factor of $k = 2$.

4 SUMMARY

With an experimental optoelectronic set-up based on a femto-second laser, the authors succeeded to determine the absolut time delay caused by the photo-electric conversion and amplification of a set of photodetectors. The determined delay time of 3.10(8) ns transformes to a phase difference of 0.022° at a frequency of 20 kHz when the photo diodes are used for their original purpose, the calibration of accelerometers or laser vibrometers. Compared to other uncertainty components in these calibration set-up, this can be considered negligible. However, up to now, the amount of the time delay was only estimated on the basis of assumptions concerning the system response of the photodiode preamplifiers, the bandwidth and rise time of the devices. With the reported measurements, it has been directly experimentally demonstrated for the first time.

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